

Prospects for Indirect Detection of Dark Matter with CTA

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We discuss the prospects for indirect detection of dark matter (DM) with the Cherenkov Telescope Array (CTA), a future ground-based gamma-ray observatory that will be sensitive to gamma rays in the energy range from a few tens of GeV to 100 TeV. We consider the detectability of DM annihilation in different astrophysical targets with a focus on the Galactic Center (GC) region. With a deep observation of the GC, CTA will be sensitive DM particles with mass greater than 100 GeV and an annihilation cross section close to the thermal relic value.

Introduction. Strong evidence indicates that most of the matter in the Universe is dark. Indeed, in the standard cosmology, $\sim 27\%$ of the Universe consists of non-baryonic dark matter (DM) [1]. DM has not been conclusively detected in the laboratory yet, but its gravitational effects have been observed on spatial scales ranging from the inner kiloparsecs of galaxies out to Mpc and cosmological scales. Also, the only way to explain the formation of large scale structure is by requiring that the dominant component of matter in the Universe is cold DM. Observations of separate distributions of the baryonic and gravitational mass in galaxy clusters indicate that the DM is likely composed of particles with a low interaction cross section relative to ordinary matter. Particle physics theory predicts degrees of freedom for new particles at the 100 GeV to 10 TeV scale to solve the hierarchy problem in the Standard Model [2]. Remarkably, weakly interacting 100 GeV-scale particles would naturally result in the correct relic abundance. The concordance of the diverse astrophysical data, together with compelling theoretical arguments provide a strong case for DM searches aimed at the detection of a thermal relic with weak-scale interactions with ordinary matter.

One of the most popular candidates for DM is the class of models known as weakly interacting massive particles (WIMPs). In regions of high DM density the annihilation (or decay) of WIMPs into Standard Model particles could produce a distinctive signature in gamma rays potentially detectable with ground- and space-based gamma-ray observatories. In fact, almost any annihilation channel will eventually produce gamma-rays either through pion production (for hadronic channels), or final state bremsstrahlung and inverse Compton from leptonic channels. Moreover, the spectrum from annihilation would be universal, with the same distinctive shape detected in every DM halo. The measurement of the gamma-ray signature would also complement direct searches by providing a strong constraint on the WIMP mass. A detection with both techniques would uniquely reveal both the mass and scattering cross section of the WIMP particle.

The planned Cherenkov Telescope Array (CTA) [3] is designed to have sensitivity over the energy range from a few tens of GeV to 100 TeV. To achieve the best sensitivity over this wide energy range CTA will include three telescope types: Large Size Telescope (LST, 23 m diameter), Medium Size Telescope (MST, 10-12 m) and Small Size Telescope (SST, 4-6 m). Over this energy range the point-source sensitivity of CTA will be at least one order of magnitude better than current generation imaging atmospheric Cherenkov telescopes such as H.E.S.S., MAGIC, and VERITAS. CTA will also have an angular resolution at least 2–3 times better than current ground-based instruments, improving with energy from 0.1° at 100 GeV to better than 0.03° at energies above 1 TeV.

Targets for Indirect DM Searches. The gamma-ray flux from DM annihilations scales with the integral of the square of the DM density along the line of sight to the source (J). Thus, the detectability of the DM signal from a given target depends critically on its DM distribution. The ideal targets for DM annihilation searches are those that have both a large value of J and relatively low astrophysical gamma-ray foregrounds. These criteria have motivated a number of Galactic and extragalactic targets including the Galactic Center (GC), dwarf spheroidal satellite galaxies of the Milky Way (dSphs), and galaxy clusters. While the sensitivity of the signal to the DM halo profile is a source of significant systematic uncertainty, it also provides an avenue for inferring the DM halo profile from the shape of the gamma-ray emission. The detection of a distinctive

spatial morphology would definitively connect the detected particle to the missing gravitational mass in galaxies.

The GC is expected to be the brightest source of DM annihilations in the gamma-ray sky by at least two orders of magnitude. Although the presence of many astrophysical sources of gamma-ray emission toward the inner Galaxy make disentangling the DM signal difficult in the crowded GC region, the DM-induced gamma-ray emission is expected to be so bright there that one can realize strong upper limits at the level of the natural cross section $\langle\sigma v\rangle \sim 10^{-26}\text{cm}^3\text{s}^{-1}$. In addition, with the improved angular resolution of CTA, the astrophysical foregrounds can be more easily identified and separated from the diffuse annihilation signal. Also, the large concentration of baryons in the innermost region of the Galaxy might act to further increase the expected DM annihilation flux by making the inner slope of the DM density profile steeper [4]. While the exact role of baryons is not yet well understood, new state-of-the-art numerical studies of structure formation that include baryonic physics along with the non-interacting DM are beginning to provide valuable insights [5, 6].

N-body simulations of galactic structure formation show the evolution of the cold DM distribution from an initial state of almost homogeneous density into a present epoch of hierarchically assembled clustered state embedded into a main smooth galactic halo [7]. The mass range of this wealth of subhalos spans all resolved mass scales. In this context, dSphs are interpreted as large DM subhalos of the Milky Way. dSphs are attractive for DM searches in gamma rays due to their close proximity, high DM content, and the absence of intrinsic sources of gamma-ray emission. Because they are highly DM-dominated, the DM mass on small spatial scales (~ 100 pc) can be directly inferred from measurements of their stellar velocity dispersions. The uncertainty of the line of sight distribution of DM for these systems is therefore much less than for other candidates. Additionally, smaller DM subhalos may not have attracted enough baryonic matter to ignite star-formation and would therefore be invisible to most astronomical observations from radio to X-rays. All-sky monitoring instruments sensitive at gamma-ray energies, like Fermi-LAT, may detect the DM annihilation flux from such subhalos [8], while follow-up observations with CTA would characterize the distinctive spectral cut-off that would eventually determine the DM particle mass (see CF2/CF6 whitepaper *Search for Dark Matter Sub-Halos in the Gamma-ray Band* for further discussion of this strategy).

Galaxy clusters are another potential class of extragalactic targets for DM searches. The best candidates are nearby galaxy clusters such as Virgo, Fornax, Perseus, and Coma. Evaluated on the basis of the smooth DM component, the annihilation signals of the best galaxy cluster candidates are fainter on average than for dSphs. Yet, when the contributions from DM subhalos are included the expected DM signals from these systems could be significantly greater [9]. In contrast, this substructure boost is expected to be only a small effect for dSphs and the GC.

Current Constraints on the DM Annihilation Cross Section. Searches for the DM gamma-ray annihilation signature have been conducted by all current ground-based Cherenkov telescope observatories, H.E.S.S., MAGIC, and VERITAS. VERITAS and MAGIC have conducted several observation campaigns on northern hemisphere dSphs including Coma Berenices, Willman I, Draco, Ursa Minor, and Segue 1 [12–15] while H.E.S.S. has conducted observations of the southern hemisphere dSphs Sagittarius, Canis Major, Sculptor, and Carina [16–18]. A search for a DM signal in the annular region of 0.3° – 1.0° around the GC conducted using 112 h of H.E.S.S. observations [19] currently sets the most constraining limits on the DM annihilation cross section for WIMP masses above 1 TeV, reaching $\sim 7 \times 10^{-25} \text{ cm}^2 \text{ s}^{-1}$ at 1 TeV for WIMPs annihilating through the bb channel (Fig. 1).

The data from the Large Area Telescope (LAT) on the *Fermi* satellite have been used to search for DM annihilations in the energy range 100 MeV – 100 GeV by looking for signatures of point-like emission in dSphs [20] and galaxy clusters as well as diffuse gamma-ray emission from the Galactic DM halo [21, 22] and from DM annihilation at cosmological distances [23]. The upper limits on the annihilation cross section derived from the analysis of dSphs are among the most constraining for WIMP models with masses below 300 GeV. As compared with searches for DM signatures in the Milky Way halo, these limits also have smaller systematic uncertainties associated with modeling astrophysical foregrounds and the DM distribution in the

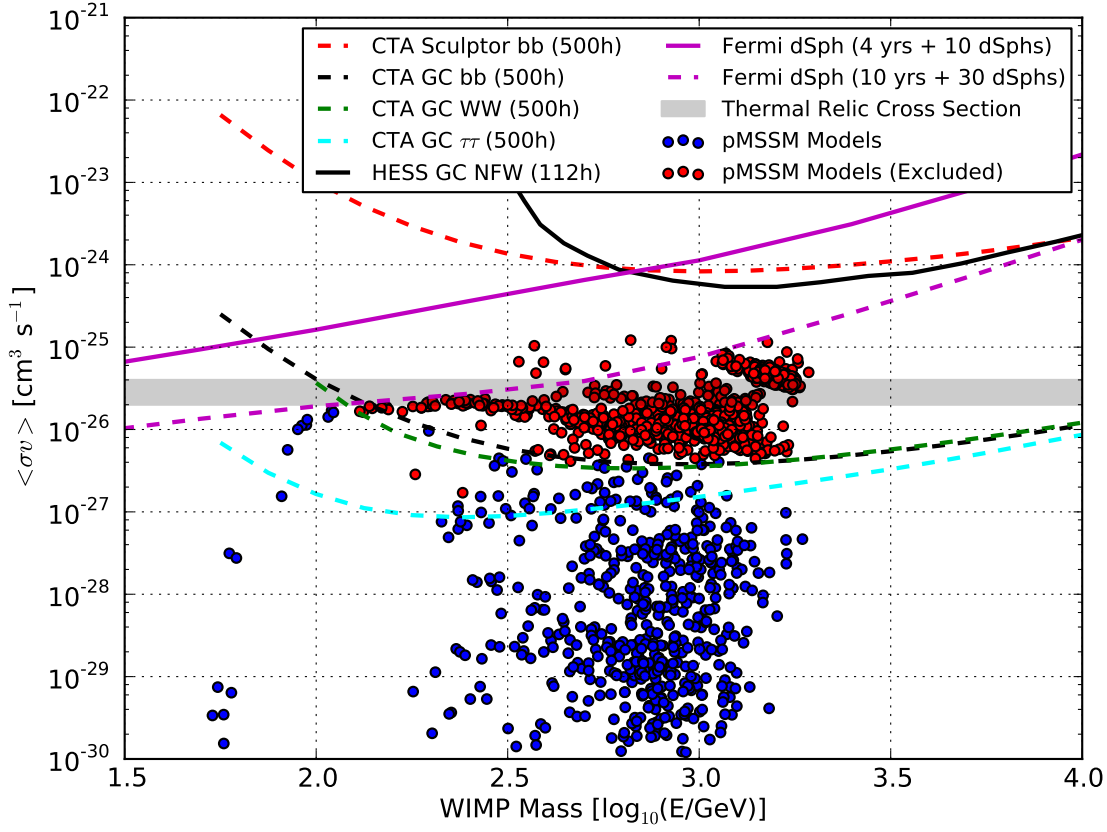


FIG. 1. Comparison of current (solid lines) and projected (dashed lines) limits on the DM annihilation cross section from different gamma-ray searches as a function of WIMP mass. Limits for Fermi (magenta lines) and H.E.S.S. (solid black line) are calculated for a 100% branching ratio to bb . Projected limits for CTA are shown for WIMP annihilation to bb and a 500 hour observation of Sculptor (red dashed line) and for WIMP annihilation to bb (black dashed line), W^+W^- (green dashed line), and $\tau^+\tau^-$ (cyan dashed line) and a 500 hour observation of the GC. The calculation of the annihilation flux for the GC region assumes an NFW MW halo profile with a scale radius of 20 kpc and DM density at the solar radius of 0.4 GeV cm^{-3} . Filled circles represent pMSSM models satisfying WMAP7 constraints on the relic DM density and experimental constraints from ATLAS and CMS SUSY searches and XENON100 limits on the spin-independent WIMP-nucleon cross section [10, 11]. Models indicated in red would be excluded by the CTA 95% C.L. upper limit from a 500 hour observation of the Galactic Center.

target region. Figure 1 shows upper limits on the annihilation cross section derived from a combined analysis of 10 dSphs and 4 years of LAT data. These are among the most stringent limits on the DM annihilation cross section obtained so far by any technique (including the LHC, or direct detection experiments). Also shown in the figure is the projected LAT limit with 10 years of data and an additional 20 dSphs which could be discovered in future optical surveys.

Projected Sensitivity of CTA for DM Searches. The potential of CTA for DM searches and testing other exotic physics has been studied in detail by [24] using the projected performance of several alternative array configurations [25] with 18–37 MSTs and different combinations of SSTs and LSTs. For the study presented here we have considered the performance of a candidate CTA configuration with 61 MSTs corre-

sponding to the baseline MST array with an additional US contribution of 36 MSTs [26]. This configuration has comparable point-source sensitivity to previously studied CTA configurations below 100 GeV but **2–3 times better point-source sensitivity between 100 GeV and 1 TeV.**

Figure 1 shows the projected sensitivity of our candidate CTA configuration to a WIMP particle annihilating through three possible final states: bb , W^+W^- , and $\tau^+\tau^-$. For the Sculptor dSph, one of the best dSph candidates in the south, CTA could reach $\sim 10^{-24} \text{ cm}^2 \text{ s}^{-1}$ at 1 TeV which is comparable to current limits from H.E.S.S. observations of the GC halo. For an observation of the GC utilizing the same $0.3^\circ\text{--}1.0^\circ$ annular search region as the H.E.S.S. analysis CTA could rule out models with cross sections significantly below the thermal relic cross section down to $\sim 3 \times 10^{-27} \text{ cm}^2 \text{ s}^{-1}$. Overlaid in the figure are WIMP models generated in the pMSSM framework that satisfy all current experimental constraints from collider and direct detection searches [10, 11]. **Approximately half of the models in this set could be excluded at the 95% C.L. in a 500 hour observation of the Galactic center.**

Key Questions and Complementarity with other Techniques. For the purpose of planning for the U.S. HEP community to form a balanced DM program, we address several key questions: (1) *What are the principal uncertainties in the technique? What would it take to make a convincing detection?* Gamma-rays provide excellent calorimetry for almost any annihilation channel, with a detection cross section that is closely related to the total annihilation cross section that determines the relic abundance. Unlike direct detection where the cross-section uncertainties dominate, astrophysical uncertainties dominate gamma-ray measurements. For dSphs, these are largely mitigated by the lack of astrophysical backgrounds, and improving constraints on the halo profile from dynamical measurements. However, for the GC, where the prospects for detection are best, these uncertainties are the largest. For example, comparing our baseline NFW MW halo model with the most pessimistic case of a cored isothermal profile, we calculate a variation of a factor of ~ 30 in the J-factor. The most compelling signature for an actual detection would come from measuring identical spectra from *two different astrophysical sources*. (2) *Can one technique like gamma-ray detection provide the answer alone, or are other detection methods required?* Any one method (direct detection, indirect detection with gamma rays, antimatter or neutrinos) is unlikely to provide a convincing case for detection. Each potential signal brings with it the potential for a new background (a new radioactive decay channel for direct detection counting experiments, or a new astrophysical source for indirect detection). A compelling case probably requires convergent evidence from a number of different techniques. But if any accelerator experiment, or direct detection experiment, were to yield a putative signal, one clearly would need a gamma-ray experiment to connect the laboratory discovery to the actual distribution of DM on the sky, and to help identify the nature of the particle through the details of the annihilation spectrum. The ability of all detection techniques to fully encompass the WIMP parameter space also depends critically on their complementarity. For instance CTA will have a unique sensitivity to very high mass WIMPs (above 1 TeV) that would not be easily detectable with current accelerator experiments.

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- [1] Planck Collaboration, P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, *et al.*, ArXiv e-prints (Mar. 2013), 1303.5076.
- [2] J. L. Feng, ArXiv e-prints (Feb. 2013), 1302.6587.
- [3] M. Actis, G. Agnetta, F. Aharonian, A. Akhperjanian, J. Aleksić, E. Aliu, D. Allan, I. Allekotte, F. Antico, L. A. Antonelli, *et al.*, Experimental Astronomy **32**, 193 (Dec. 2011), 1008.3703.
- [4] O. Y. Gnedin, A. V. Kravtsov, A. A. Klypin, and D. Nagai, ApJ **616**, 16 (Nov. 2004), arXiv:astro-ph/0406247.
- [5] D. R. Cole, W. Dehnen, and M. I. Wilkinson, MNRAS **416**, 1118 (Sep. 2011), 1105.4050.
- [6] A. V. Macciò, G. Stinson, C. B. Brook, J. Wadsley, H. M. P. Couchman, S. Shen, B. K. Gibson, and T. Quinn, ApJ **744**, L9, L9 (Jan. 2012), 1111.5620.
- [7] J. Diemand, M. Kuhlen, P. Madau, M. Zemp, B. Moore, D. Potter, and J. Stadel, Nature **454**, 735 (Aug. 2008), 0805.1244.

- [8] M. Kamionkowski, S. M. Koushiappas, and M. Kuhlen, *Phys. Rev. D* **81**(4), 043532, 043532 (Feb. 2010), 1001.3144.
- [9] M. A. Sánchez-Conde, M. Cannoni, F. Zandanel, M. E. Gómez, and F. Prada, *J. Cosmology Astropart. Phys.* **12**, 11, 011 (Dec. 2011), 1104.3530.
- [10] J. A. Conley, J. S. Gainer, J. L. Hewett, M. P. Le, and T. G. Rizzo, *European Physical Journal C* **71**, 1697 (Jul. 2011), 1009.2539.
- [11] M. W. Cahill-Rowley, J. L. Hewett, S. Hoeche, A. Ismail, and T. G. Rizzo, *European Physical Journal C* **72**, 2156 (Sep. 2012), 1206.4321.
- [12] E. Aliu, H. Anderhub, L. A. Antonelli, P. Antoranz, M. Backes, C. Baixeras, S. Balestra, J. A. Barrio, H. Bartko, D. Bastieri, *et al.*, *ApJ* **697**, 1299 (Jun. 2009), 0810.3561.
- [13] V. A. Acciari, T. Arlen, T. Aune, M. Beilicke, W. Benbow, D. Boltuch, S. M. Bradbury, J. H. Buckley, V. Bugaev, K. Byrum, *et al.*, *ApJ* **720**, 1174 (Sep. 2010), 1006.5955.
- [14] J. Aleksić, E. A. Alvarez, L. A. Antonelli, P. Antoranz, M. Asensio, M. Backes, J. A. Barrio, D. Bastieri, J. Becerra González, W. Bednarek, *et al.*, *J. Cosmology Astropart. Phys.* **6**, 35, 035 (Jun. 2011), 1103.0477.
- [15] E. Aliu, S. Archambault, T. Arlen, T. Aune, M. Beilicke, W. Benbow, A. Bouvier, S. M. Bradbury, J. H. Buckley, V. Bugaev, *et al.*, *Phys. Rev. D* **85**(6), 062001, 062001 (Mar. 2012), 1202.2144.
- [16] F. Aharonian, A. G. Akhperjanian, A. R. Bazer-Bachi, M. Beilicke, W. Benbow, D. Berge, K. Bernlöhr, C. Boisson, O. Bolz, V. Borrel, *et al.*, *Astroparticle Physics* **29**, 55 (Feb. 2008), 0711.2369.
- [17] F. Aharonian, A. G. Akhperjanian, U. B. de Almeida, A. R. Bazer-Bachi, B. Behera, W. Benbow, K. Bernlöhr, C. Boisson, V. Bochov, V. Borrel, *et al.*, *ApJ* **691**, 175 (Jan. 2009), 0809.3894.
- [18] H.E.S.S. Collaboration, A. Abramowski, F. Acero, F. Aharonian, A. G. Akhperjanian, G. Anton, A. Barnacka, U. Barres de Almeida, A. R. Bazer-Bachi, Y. Becherini, *et al.*, *Astroparticle Physics* **34**, 608 (Mar. 2011), 1012.5602.
- [19] A. Abramowski, F. Acero, F. Aharonian, A. G. Akhperjanian, G. Anton, A. Barnacka, U. Barres de Almeida, A. R. Bazer-Bachi, Y. Becherini, J. Becker, *et al.*, *Physical Review Letters* **106**(16), 161301, 161301 (Apr. 2011), 1103.3266.
- [20] M. Ackermann, M. Ajello, A. Albert, W. B. Atwood, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, K. Bechtol, R. Bellazzini, *et al.*, *Physical Review Letters* **107**(24), 241302, 241302 (Dec. 2011), 1108.3546.
- [21] M. Ackermann, M. Ajello, A. Albert, L. Baldini, G. Barbiellini, K. Bechtol, R. Bellazzini, B. Berenji, R. D. Blandford, E. D. Bloom, *et al.*, *Phys. Rev. D* **86**(2), 022002, 022002 (Jul. 2012), 1205.2739.
- [22] M. Ackermann, M. Ajello, W. B. Atwood, L. Baldini, G. Barbiellini, D. Bastieri, K. Bechtol, R. Bellazzini, R. D. Blandford, E. D. Bloom, *et al.*, *ApJ* **761**, 91, 91 (Dec. 2012), 1205.6474.
- [23] A. A. Abdo, M. Ackermann, M. Ajello, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, K. Bechtol, R. Bellazzini, B. Berenji, *et al.*, *J. Cosmology Astropart. Phys.* **4**, 14, 014 (Apr. 2010), 1002.4415.
- [24] M. Doro, J. Conrad, D. Emmanoulopoulos, M. A. Sánchez-Conde, J. A. Barrio, E. Birsin, J. Bolmont, P. Brun, S. Colafrancesco, S. H. Connell, *et al.*, *Astroparticle Physics* **43**, 189 (Mar. 2013), 1208.5356.
- [25] K. Bernlöhr, A. Barnacka, Y. Becherini, O. Blanch Bigas, E. Carmona, P. Colin, G. Decerprit, F. Di Pierro, F. Dubois, C. Farnier, *et al.*, *ArXiv e-prints* (Oct. 2012), 1210.3503.
- [26] T. Jogler, M. D. Wood, J. Dumm, and CTA Consortium, in F. A. Aharonian, W. Hofmann, and F. M. Rieger, eds., *American Institute of Physics Conference Series* (Dec. 2012), vol. 1505 of *American Institute of Physics Conference Series*, pp. 765–768, 1211.3181.